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TEMPERATURE DEPENDENCE OF THE PLANAR HALL EFFECT IN FERROMAGNETIC METALS AND ALLOYS

VU DINH KY

Moscow State University; Hanoi Polytechnical Institute

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A study was made of the temperature dependence of the planar Hall effect in nickel and iron-nickel alloys. The role of various scattering mechanisms in this galvanomagnetic effect is discussed. It is shown that in the case of nickel the main contribution to the effect is made, in the investigated temperature range, by a mechanism of intrinsic spin-orbit interaction of polarized electrons in the scattering by impurities and phonons. The experimental results for the investigated iron-nickel alloys indicate that the main contribution to the planar Hall effect is made by the scattering mechanism which is responsible for their residual resistance.

EXPRESSIONS for the planar Hall effect coefficient of ferromagnetic metals have been derived by the present author[1-3] allowing for various scattering mechanisms. It has been shown that, in the case of the scattering of carriers by impurities and phonons in crystals with a center of symmetry, the coefficient P for the planar Hall effect is given by the expression[1]

$$P = C\rho_{\mathrm{iph}}(M/M_0)^2, \tag{1}$$

where C is a constant for a given metal; ρ_{iph} is the resistivity due to the scattering by impurities and phonons; M is the magnetization at a temperature T; M_0 is the magnetization at 0°K. Thus, the temperature dependence of P is in this case determined by the temperature dependences of ρ_{iph} and M^2. If we assume that the magnetization is mainly due to nonlocalized electrons it follows that

$$C \propto (E_F E^{\mathrm{so}}/\Delta^2)^2, \tag{2}$$

where E_F is the Fermi energy; E^{so} is the energy representing the intrinsic spin-orbit interaction; Δ is the average distance between sub-bands in the spectrum of the electron system. For nickel, $E_F \approx 10^{-12}$ erg, $E^{\mathrm{so}} \approx 10^{-13}$–$10^{-14}$ erg, and $\Delta \approx 10^{-12}$ erg, so that $C \approx 10^{-2}$.

Calculations concerned with the mechanism of scattering by magnetic inhomogeneities in the s-d interaction model have shown that the temperature dependence of the planar Hall coefficient is the same as the temperature dependence of the "magnetic" resistance, i.e., the coefficient increases when the temperature is increased, passes through a maximum in the direct vicinity of the Curie temperature, and then decreases steeply.[2,3]

The present paper reports the results of an experimental investigation of the planar Hall effect in nickel and iron-nickel alloys. The results are used to consider the role of various scattering mechanisms in the planar Hall effect. The temperature dependence of the Hall effect was investigated in the temperature range from liquid nitrogen to T ≈ 500°C. Above room temperature, the samples were heated in a furnace and measurements were carried out in 10^{-2}–10^{-3} mm Hg vacuum; below room temperature, the samples were placed in an atmosphere of nitrogen vapor. The temperature was measured with a constantan-copper thermocouple.

According to[1,4], the planar Hall effect is given by the expression

$$V_y = P\frac{I}{t}\sin\varphi\cos\varphi, \tag{3}$$

where P is the planar Hall effect coefficient; I is the current; t is the thickness of the sample; φ is the angle between the current density vector and the magnetization in the plane of the sample; V_y is the resultant transverse potential difference. The value of P can be deduced from Eq. (3):

$$P = \frac{t}{I}\left[V_y\left(\varphi = \frac{\pi}{4}\right) - V_y\left(\varphi = -\frac{\pi}{4}\right)\right]. \tag{4}$$

The investigated samples were magnetized to saturation by placing them in a field of 1 kOe. Since the absolute saturation magnetization (the "paraprocess") became stronger in the vicinity of the Curie temperature, the values of P were found in this range of temperature by extrapolating the field to zero. In most cases, the estimated error in the determination of P did not exceed 5%.

Figure 1 shows the dependence of P on T for 99.9% pure nickel. A maximum of P can be seen at a temperature of ~120°C. Figure 1 shows a tail in the region of the Curie temperature and this tail extends above T_C. It follows also from Fig. 1 that P tends to zero (within the limits of the experimental error) at temperatures above T_C. The form of the dependence of P on T shown in Fig. 1 cannot be explained by assuming that the scattering by magnetic inhomogeneities plays the main role in the planar Hall effect in nickel since in such a case a maximum should have been observed in the direct vicinity of the Curie point.[2,3] On the other hand, the form of the P(T) curve in Fig. 1 can be explained satisfactorily using Eq. (1). According to Eq. (1), the temperature dependence of P is governed by the temperature dependences of ρ_{iph} and of the spontaneous magnetization M. When the temperature is increased (starting from liquid nitrogen temperature), initially an increase in ρ_{iph} predominates over a decrease of M so that P increases. However, above a certain temperature $T_{\max}$,

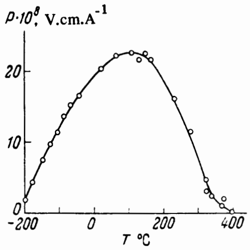

FIG. 1. Temperature dependence of P for nickel.

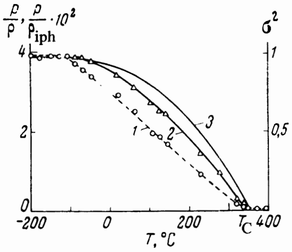

FIG. 3. Temperature dependences of: 1 – P/ρ; 2 – P/ρ_{iph}; 3 – σ^2 of Ni.

the fall of M begins to predominate and consequently P decreases. Above the Curie point, the values of M and, therefore, of P both tend to zero.

We can also find the temperature dependence of P/ρ_{iph} by subtracting ρ_{iph} from the total resistivity ρ using a method described by Weiss and Marotta.[5] To do this, we have simultaneously to measure P and ρ. The separation of ρ into ρ_{iph} and the "magnetic" resistivity ρ_m is shown in Fig. 2.

The results presented in Figs. 1 and 2 can be used to plot the temperature dependences of P/ρ and P/ρ_{iph}, which are given in Fig. 3. Figure 3 includes also the curve $\sigma^2(T)$ plotted using the formula ($\sigma = \tanh(\sigma/\Theta)$, where $\sigma = M/M_0$ and $\Theta = T/T_C$. In plotting these data, we have assumed that P/ρ is unity at liquid nitrogen temperature. If we assume, as usual, that the standard formula for σ can be applied to nickel, it follows from Fig. 3 that the nature of the $\sigma^2(T)$ curve is similar to the temperature dependence of P/ρ_{iph}. This confirms the validity of Eq. (1) in the case of nickel.

The discrepancy between the σ^2 and P/ρ curves in Fig. 3 is greater at temperatures higher than $T \approx -90^\circ C$. This is because above this temperature the quantities ρ and ρ_{iph} differ considerably. Making allowance for this circumstance, ρ in Fig. 2 should be divided into its components from $T \approx -90^\circ C$ rather than from some arbitrary temperature, as has been done by Weiss and Marotta.[5]

The value of T_{max} can be found using Eq. (1) and the expressions for M and ρ_{iph}. At high temperature, we can always write $\rho_{iph} \propto (\Theta - \Theta_0)$. Differentiating Eq. (1), we can easily obtain an equation which defines Θ_{max}:

$$\frac{\Theta_{max}}{3\Theta_{max} - 2\Theta_0} = 1 - \sigma^2. \tag{5}$$

In this case, it follows from Fig. 2 that $\Theta_0 \approx 0.084$. Solving Eq. (5) graphically, we find that $\Theta_{max} \approx 0.64$, i.e., $T_{max} \approx 403^\circ K$ or 130°C. This value is in good agreement with the experimental data (Fig. 1).

The value of P/ρ at liquid nitrogen temperature is 4×10^{-2} (Fig. 3). Since, at this temperature, we can assume that $M \approx M_0$ (within the limits of the experimental error), it follows that $P/\rho \approx C$. Thus, the experimental value of P/ρ is of the same order as the estimate given earlier for nickel.

All the results indicate that the scattering by phonons and impurities plays the main role in the planar Hall effect in nickel. The scattering by magnetic inhomogeneities in the model of localized magnetic electrons makes no appreciable contribution. This can be explained by the fact that, according to this model, the constant of the spin-orbital interaction between magnetic and conduction electrons is relatively small and the contribution to the planar Hall effect is of the order of the second power of this constant. We must mention that according to [6] this constant is in fact larger than would follow from an estimate obtained on the basis of the free-electron model. However, in the case of nickel, our experimental results show that this circumstance has little influence on the planar Hall effect.

The low-temperature value of P/ρ for nickel is also in agreement with the results of measurements of the resistivity anisotropy reported by Smit.[7] Since $P = \Delta\rho_s$ for an isotropic polycrystalline sample ($\Delta\rho_s$ is the resistivity anisotropy), it follows that $P/\rho = \Delta\rho_s/\rho$. Smit[7] has found that for Ni $\Delta\rho_s/\rho \approx 3 \times 10^{-2}$ at liquid hydrogen temperature. Smit has determined $\Delta\rho_s$ by measuring the resistivity but he has not measured the temperature dependence of $\Delta\rho_s$. The measurement of P by the planar Hall effect method (the measurement of the transverse potential difference) used in the present investigation is much more convenient and accurate than the measurement of $\Delta\rho_s$ by the standard method. In the standard method, we have to measure the resistivity along two mutually perpendicular directions of a strong field and then we have to extrapolate the "paraprocess" curves to a field $H = 0$.

Figure 4 shows the dependences of P on T for some iron-nickel alloys. In contrast to the $P(T)$ curve for nickel, the value of P of these alloys decreases monotonically when the temperature is increased. This result shows that only M^2 and not the resistivity governs the temperature dependence of P of these alloys. The value of P decreases because M^2

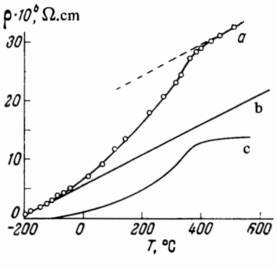

FIG. 2. Separation of ρ into ρ_{iph} and ρ_m for nickel: a – ρ; b – ρ_{iph}; c – ρ_m.

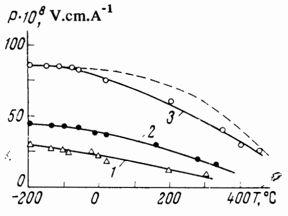

FIG. 4. Temperature dependences of P of iron-nickel alloys: 1 – 45% Ni; 2 – 65% Ni; 3 – 82% Ni.

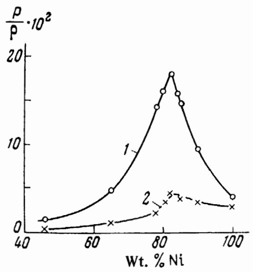

FIG. 5. Dependences of P/ρ on the composition of iron-nickel alloys at liquid nitrogen temperature (1) and at room temperature (2).

falls when T is increased. Figure 4 includes, in addition to the $P(T)$ curve for an 82% Ni alloy, a dashed curve $\sigma^2(T)$ which has been plotted on the assumption that $T_C = 830°K$ for this alloy[8] and that P is unity at liquid nitrogen temperature. The results obtained cannot be accounted for using Eq. (1) but they are in agreement with a theory developed in[1] provided we assume that - in contrast to nickel - the main contribution to the planar Hall effect in these alloys is made by the scattering which is responsible for their residual resistance, i.e., that the scattering by phonons is unimportant.

Dependence of the value of P/ρ on the alloy composition at room temperature and at liquid nitrogen temperature is of great interest (Fig. 5). At liquid nitrogen temperature, the maximum is sharper and occurs in the 81–83% Ni composition range. Smit[7] has also found a $\Delta\rho_s/\rho$ maximum in the same range of compositions but at liquid hydrogen temperature. On qualitative grounds, Berger[9] has attributed this maximum to the s–d Mott transition mechanism, in which an allowance is made for the spin-orbital interaction, and he has assumed that two d sub-bands overlap near the Fermi surface. However, it is known that the s-d Mott transition mechanism can hardly be applied to iron-nickel alloys.[10] In spite of this, Berger's suggestion about the overlap of the d sub-bands near the Fermi surface can be used in conjunction with Eq. (2) to account for the maximum observed in Fig. 5. In fact, it follows from Eq. (2) that P/ρ_i (ρ_i is the resistivity due to the scattering by impurities and at low temperatures $\rho \approx \rho_i$) is inversely proportional to Δ^4. Thus, for compositions with 81–83% Ni the value of Δ decreases considerably because of the overlap of the d sub-bands and, therefore, P should increase strongly at these concentrations.

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